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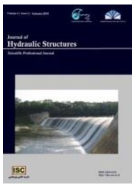

Enhancing the seismic performance of platforms in intermediate water depth using shape memory alloy dampers

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Abstract

Wharves supported by vertical piles are very common marine structures with suitable seismic responses. Nevertheless, they severely suffer from extensive lateral displacement in both design and service earthquake level state. Conversely, wharves with batter piles have limited displacement, but they are often restricted by numerous standards and guidelines due to the significant seismic base shear and undesirable failure modes such as buckling, pullout, and deck punching. This study aims to assess the efficacy of shape memory alloy (SMA) based dampers in controlling both displacement and seismic base shear within acceptable limits. To achieve this goal, a thorough investigation is conducted on an oil terminal platform, located north of Qesh in Iran, with a water depth of 20m, as a real case study. A structural system consisting of vertical and batter piles equipped with SMA dampers and base isolators is proposed, wherein batter piles were not directly connected to the deck. At first, three common scenarios (vertical piles, combination of vertical and batter piles, and friction dampers) are examined, and then the proposed SMA damper system is comprehensively evaluated and compares with the available solutions. The findings reveal that systems employing SMA dampers exhibit significantly reduced seismic base shear (20% reduction) and lateral displacement (68% reduction) compared to those with vertical piles. Additionally, the lateral displacement observed in systems utilizing SMA dampers falls within the range of those employing batter piles, while the seismic base shear is limited to only 40% of the system with batter piles.

Keywords: SMA, damper, wharves, batter piles, vertical piles.

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1. Introduction

Wharves and platform have been widely constructed in Iran to import or export different materials. Among these marine structures, oil and gas platforms with jetty access bridges are utilized for docking large tankers, in variable water depths ranging from 10m to 20m. Typically,

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these structures are pile-supported platforms including concrete decks and batter/vertical piles. Among different loads on marine structures, wave and earthquake imposes large lateral displacements that must be limited to an allowable range to ensure the operational integrity of the superstructures. Particularly in earthquake, the dual challenges of displacement and ductility become prominent. For instance, structures employing ductile components like vertical piles often suffer from excessive top-deck displacement, interrupting the structure's serviceability not only during design earthquakes but also under service-level seismic events. Conversely, structures equipped with batter piles exhibit a more tolerable range of displacement but display inadequate seismic performance [1]. Accordingly, most of standards and recommendations discourage the use of batter piles in wharves [1], and it is recommended to design the structure in elastic level in the presence of batter piles [1]. The primary inappropriate failure mechanisms associated with batter piles include pull-out from the soil, pile buckling, pile-to-deck separation, and deck punching effects [2].

In recent earthquakes, wharves with batter piles were experienced more serious damages in comparison with vertical piles [3]. For instance, pile-deck separation in batter piles were observed in Chilie earthquake at 2010 [4]. Additionally, research by [5] has highlighted the undesirable effect of vertical load carried by batter piles which reduces their performance during earthquake. Consequently, numerous studies have been developed to enhance seismic resilience of pile-supported structures, while keeping lateral displacement within acceptable range [5]. Generally, three strategies of employing fuses, dampers, isolators, or combinations them have been explored in the literature to enhance the seismic response of these structures.

Improvement in seismic response and reduction in displacement by utilizing viscous damper in combination with batter piles were investigated in [6]. It was also indicated in [6] that maintaining the displacement of structures within acceptable limits solely through the use of vertical piles (without additional measures) is very expensive. Friction dampers [7] and semi-active hydraulic dampers [8] have been successfully deployed in offshore jackets to regulate displacement [7]. Notably, friction dampers have also been employed to mitigate platform vibration caused by wave motion [9].

Experimental studies show the crucial role of connections on seismic response of the wharves [10]. Accordingly, a simple idea to improve seismic responses is to use scarified fuses in connections. Incorporation of yielding fuses in combination with batter piles has demonstrated a more flexible response characterized by ductile failure mechanisms in both the fuses and vertical piles [11]. Various investigations focusing on shear [12] and flexural [13] fuses have indicated a reduction in base shear within structures during seismic events.

Furthermore, utilizing LRB isolators in conjunction with batter piles has been explored in wharves, aiming to decrease the seismic base shear of the structure as documented in [14]. Additionally, viscous isolators have been studied for offshore jackets in China, aiming to improve the dynamic response of these structures. [15]The primary effects of isolators include elongating the period and managing torsion within structures [16], as well as ensuring uniform distribution of force among various piles [17]. The integration of base isolators alongside viscous dampers resulted in a notable reduction of 31% in displacement and 48% in base shear in Resalat jacket in the Persian Gulf [18].

As previously mentioned, in oil terminals containing sensitive equipment, both reduction in lateral displacement and base shear ensure operational integrity and safety. Recently, there has been significant development in SMA dampers exhibiting super-elastic properties, aimed at enhancing seismic response with minimal permanent displacement. MRF-SMA dampers [19] and combination of friction and SMA dampers [20] have been effectively used in offshore jackets. However, to the authors' knowledge, no study has yet assessed the effectiveness of SMA dampers in wharves. Accordingly, this study investigates the effect of SMA dampers on platforms supported by vertical/batter piles without bracing systems, in 20m water depth where suitable for common oil tankers, to control both lateral displacement and base shear in earthquake.

The manuscript is structured as follows: Theoretical backgrounds are discussed in Section 2, and assumptions of modeling are presented in Section 3. Sections 4-6 express the proposed system, which is evaluated through static pushover and dynamic analysis. The findings are summarized in Section 7.

2. Theory

2.1. Piles and Decks

Wharves or platforms are type of marine structures used for mooring ships, constructed from concrete decks supported by steel piles (Figure 1). Typically, in these structures, vertical loads are transferred to the soil through deep piles embedded into the ground. The deck, which is supported by the piles, typically works to evenly distribute the applied loads onto the piles. Common resisting systems against lateral loads are vertical and/or batter piles. The structures are classified into rigid or flexible structures based on their stiffness against lateral loads. The degree of flexibility of these structures depends on the type of materials, soil conditions, and type of structural system [1]. Marine structures are comprehensively affected by lateral wave, wind and seismic loads. Among them, the presented study is focused on the seismic load as worst case in south of Iran.

Common practice to withstand seismic loads is to use the vertical piles with flexural behavior. These types of structures exhibit desirable flexibility with minimal seismic base shear. Additionally, in many cases, vertical pile systems are very cost-effective and offer greater feasibility in terms of construction. Therefore, they are preferred option for wharves and platforms. However, the important challenge with these types of structures, in water depths between 10 to 20 meters, is significant displacements under wave, wind, and earthquake loads, severely affecting the superstructure. On the other hand, a common alternative to overcome this challenge is to use batter piles with acceptable stiffness to control displacement. But batter piles show extremely undesirable seismic response. Accordingly, in this research, the effect of SMA dampers on improving seismic behavior and reducing displacements of platforms is investigated.

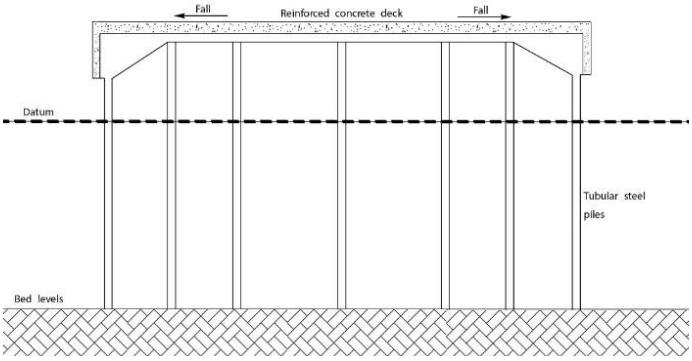


Figure 1. Wharf Supported by Vertical Piles

2.2. Shape Memory Alloys

Shape Memory Alloys (SMAs) are intelligent and innovative materials that, due to their unique behaviors, have found various applications in different fields of science and engineering in recent decades. They play a fundamental role in the development and implementation of smart materials devices. When integrated into the structures, they provide functionalities such as sensing, energy dissipation, monitoring, self-adapting, and structural repair [21].

The reversible phase change capability of these alloys allows them to endure significant shape changes and, depending on the temperature and applied stress conditions, return to their original shape when loaded or subjected to heat. This capability, accompanied by changes in mechanical, thermal, and electrical properties, has made shape memory alloys a suitable option for use in smart, advanced, and adaptive structures. When used in civil structures, these materials can reduce the damage caused by earthquakes as passive, semi-active, or active elements [21].

Until now, various types of shape memory alloys (SMAs) have been recognized. The most commonly used SMA in the industry is nickel-titanium alloy, also known as nitinol (NiTi), which is utilized in the construction for seismic applications such as passive vibration control and energy dissipation. However, the high cost of production and processing of this alloy has been reduced its widespread use in large-scale construction projects. In recent years, iron-based shape memory alloys (Fe-SMAs) have obtained significant attention in civil engineering due to their desirable properties for structural applications and reasonable cost. The recent progress in manufacturing and understanding of these alloys has expanded their application for the repair and strengthening of structures using pre-stressed Fe-SMA tendons [21].

Shape memory alloys exist in two crystalline phases called austenite and martensite. The austenite phase is the primary phase with high symmetry and stability at high temperatures and low stresses. On the other hand, the martensite is a phase with lower symmetry and stability at low temperatures and high stresses. By applying thermal or mechanical loading, these two phases can transform into each other. This reversible transformation of phases is called martensitic transformation, which affects all the characteristics of shape memory alloys, presenting them as smart materials [21]. Figure 2 illustrates martensitic transformation resulting from temperature change without applying stress. SMAs have four characteristic temperatures: As, Af, Ms, and Mf, which represent the austenite start temperature, austenite finish temperature, martensite start temperature, and martensite finish temperature, respectively. Martensitic transformations form a thermal hysteresis, meaning that direct and reverse transformations do not occur at the same temperature [21].

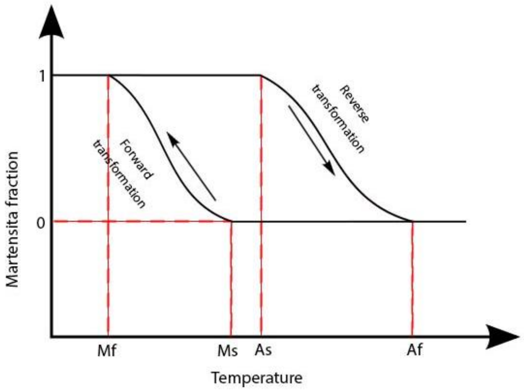


Figure 2. Martensitic transformation resulting from temperature change [21]

The stress-strain curve of this transformation, as shown in Figure 3, consists of three parts: an initial elastic branch with the initial elastic modulus of austenite, a horizontal segment where the phase transformation from austenite to martensite occurs, and again an elastic branch with the initial elastic modulus. Reverse transformation occurs during unloading and material returns to its initial shape without any residual strain. The reverse transformation along a different path forming a hysteresis loop representing the energy dissipation. This behavior is called superelastic or pseudoelastic behavior, because of zero residual strain in this loop [21].

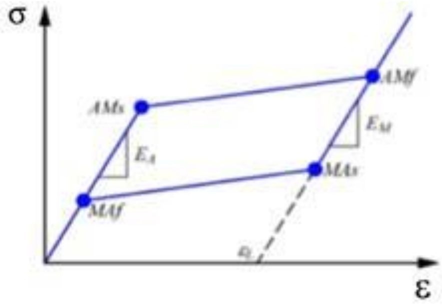


Figure 3. stress-strain carve of SMA [21]

When SMA is in the martensitic state under stress greater than the yield stress, due to the gradual reorientation of martensitic variants, it shows a high energy dissipation capacity, as depicted in Figure 4. Clearly, a large hysteresis loop is seen in this figure during cyclic loading and unloading. The mentioned crucial property of SMAs has led to attract special attention in passive control of structures. The energy dissipation capability of these materials reduces demand on the main members of the structure, and due to the high resistance to fatigue, they can also be used after earthquakes without replacement.

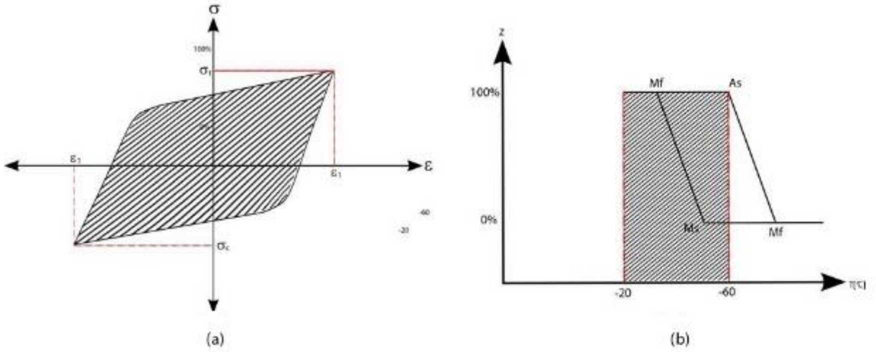


Figure 4. Martensitic Strain in SMA (a) Hysteresis Diagram (b) Martensitic Strain Temperature diagram at Zero Stress (Parameter Z refers to the martensite ratio and T refers to temperature) [21]

3. Assumptions of Modeling

3.1. Case Study of operational platform

An operational platform with area $30m \times 30m$ and 5×5 pile arrangement, as depicted in Figure 5, is investigated as a real case study in Qeshm. Height of platform from the seabed is 30 meters, with 20 meters underwater and 10 meters above the sea water level. Steel pipe piles with diameter of 1.3 meters and thickness of 19 millimeters is used. Additionally, thickness of concrete deck is 40cm, and concrete beams with dimensions of 1m×2m are considered. The properties of the materials are as shown in Table 1.

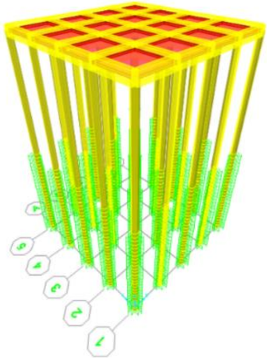


Figure 5. Model of operation platform with vertical piles in Qeshm.

Materials	Concrete	Steel (St52)
Yield stress/Compressive stress	35 MPa	360 MPa
Ultimate stress	-	520 MPa
Elastic modulus	27800 MPa	200000 MPa
Poisson’ ratio	0. 2	0. 3

3.2. Soil-Structure Interaction

In the present study, a nonlinear spring model for soil-structure interaction based on the API code [22] has been utilized, as depicted in Figure 6. In this figure, tangent and normal springs to the pile’s shaft are presented by t-z and p-y springs, respectively. Regarding the loading on the pile tip, which exhibits different behavior compared to the pile shaft, the end spring is designated as the "q-z spring".

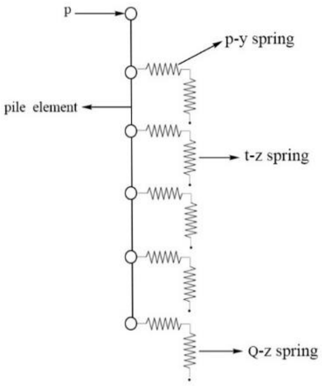


Figure 6. Soil-structure interaction for pile with p-y, t-z, and q-z springs [22]

Diagrams for p-y, t-z, and q-z springs in different levels are shown in Figure 7 to Figure 12, based on the geotechnical reports in north of Qeshm island and APIRP2 standard [22].

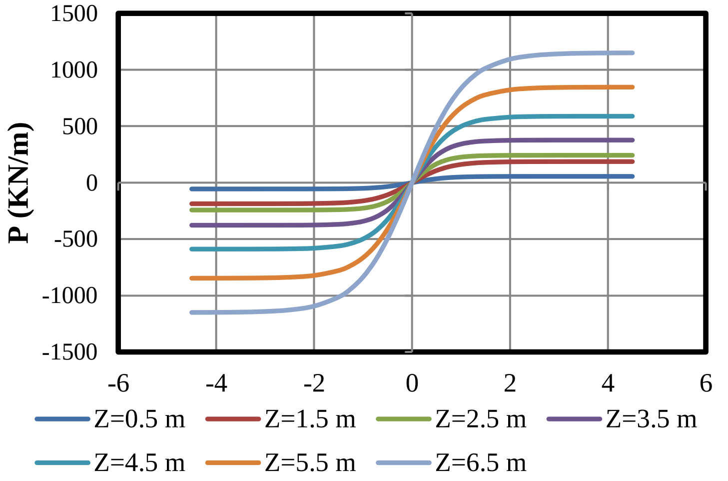


Figure 7. p-y diagram for sandy soil for 0<z< 7 from seabed.

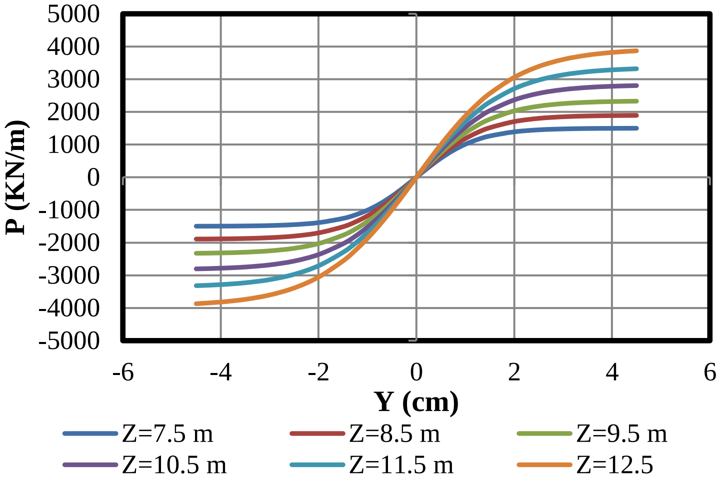


Figure 8. p-y diagram for sandy soil for 7<z<13 from seabed

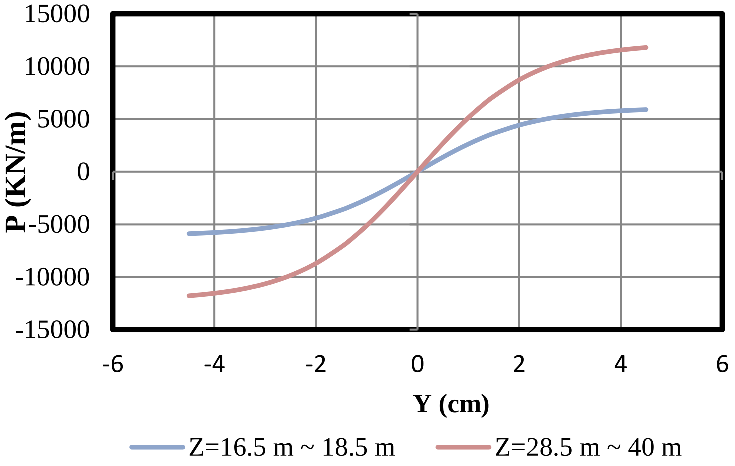


Figure 9. p-y diagram for sandy soil for z>13 from seabed.

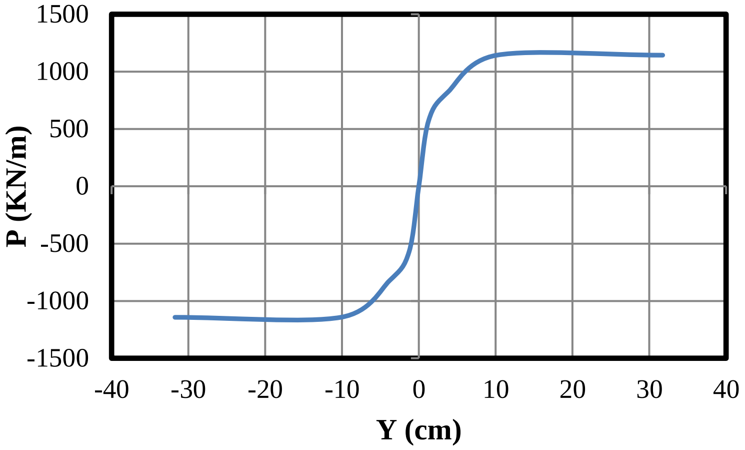


Figure 10. p-y diagram for clay.

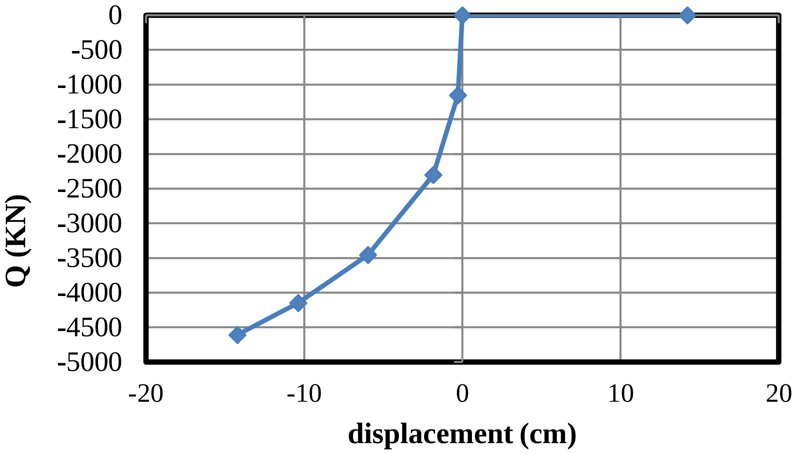


Figure 11. q-z diagram for sandy soil for 52” pile

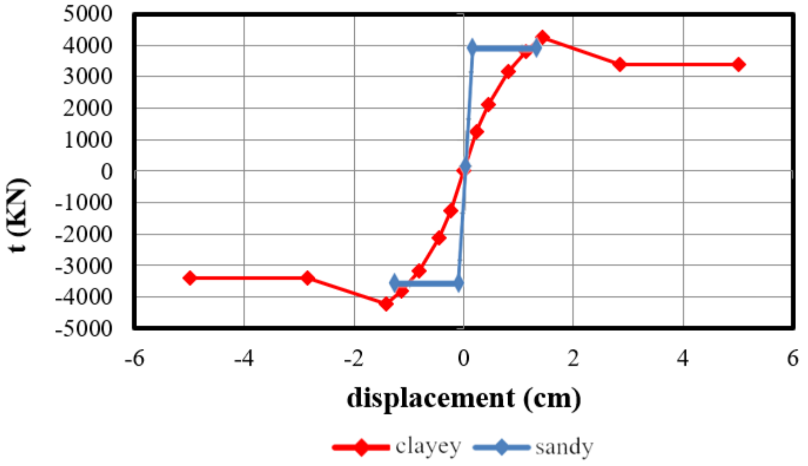


Figure 12. t-z diagram for sandy and clayey soil.

Pushover results with fixity point theory has been additionally analyzed. It should be noted that based on the OCDI recommendation, depth of fixity point is calculated as 5m as

3.3. Plastic Hinge and Acceptance Criteria

The definition and assignment of plastic hinges to steel pipe piles, as well as the criteria for failure of the hinges are considered based on the ASCE 61-14 standard [23]. As illustrated in Figure 13, the plastic hinges are defined as bilinear flexural hinges. Acceptance criterion for the joint according to the ASCE61-14 has been presented in Table 2. Additionally, the length of plastic joints according to ASCE 61-14 has been provided in Table 3.

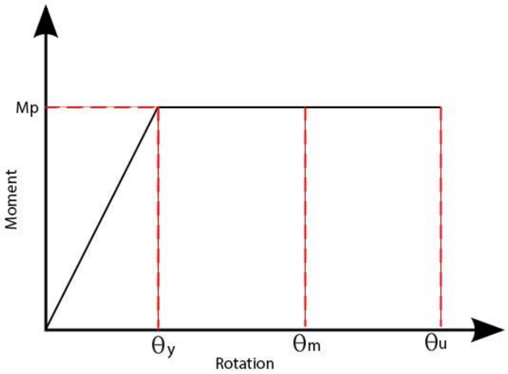
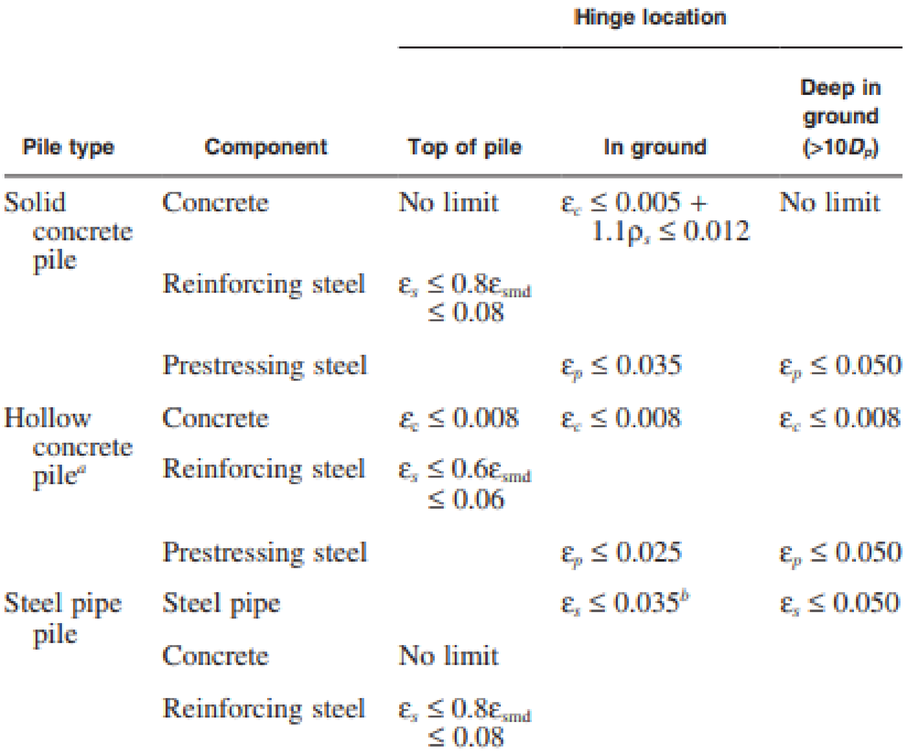


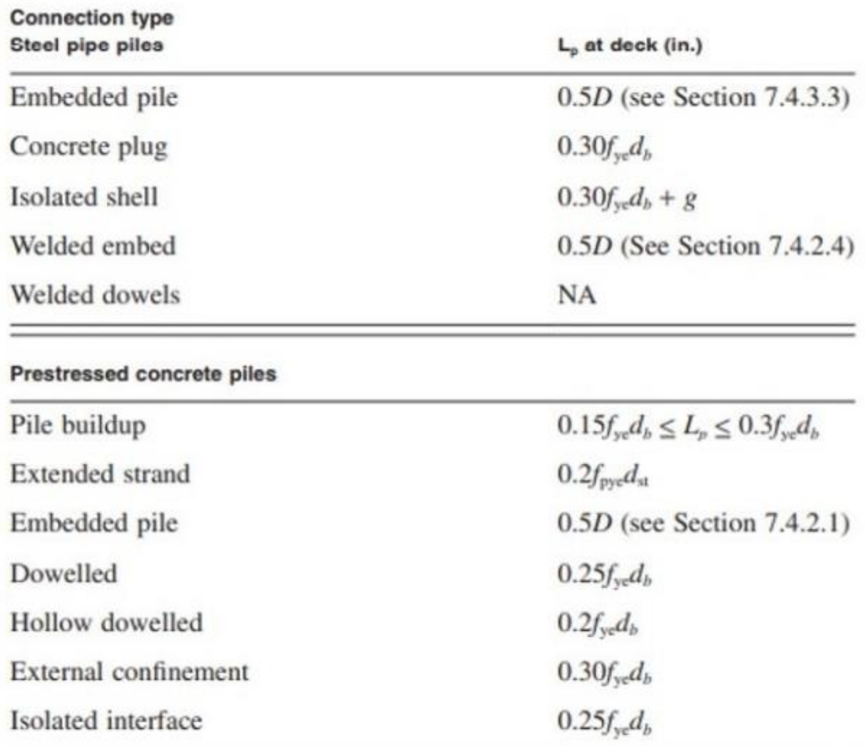
Figure 13. Flexural plastic hinge diagram for steel pile.

Table 2 - Plastic hinge acceptance criterion based on ASCE61-14 [23]



		Hinge location		
Pile type	**Component**	**Top of pile**	**In ground**	**Deep in ground (>10D_p)**
Solid concrete pile	Concrete	No limit	$\varepsilon_c \leq 0.005 + 1.1\rho_s \leq 0.012$	No limit
	Reinforcing steel	$\varepsilon_s \leq 0.8\varepsilon_{smd} \leq 0.08$		
	Prestressing steel		$\varepsilon_p \leq 0.035$	$\varepsilon_p \leq 0.050$
Hollow concrete pile[a]	Concrete	$\varepsilon_c \leq 0.008$	$\varepsilon_c \leq 0.008$	$\varepsilon_c \leq 0.008$
	Reinforcing steel	$\varepsilon_s \leq 0.6\varepsilon_{smd} \leq 0.06$		
	Prestressing steel		$\varepsilon_p \leq 0.025$	$\varepsilon_p \leq 0.050$
Steel pipe pile	Steel pipe		$\varepsilon_s \leq 0.035$[b]	$\varepsilon_s \leq 0.050$
	Concrete	No limit		
	Reinforcing steel	$\varepsilon_s \leq 0.8\varepsilon_{smd} \leq 0.08$		

Table 3 - Plastic hinge length according to ASCE 61-14[23



Connection type **Steel pipe piles**	**L_p at deck (in.)**
Embedded pile	$0.5D$ (see Section 7.4.3.3)
Concrete plug	$0.30 f_{ye} d_b$
Isolated shell	$0.30 f_{ye} d_b + g$
Welded embed	$0.5D$ (See Section 7.4.2.4)
Welded dowels	NA
Prestressed concrete piles	
Pile buildup	$0.15 f_{ye} d_b \le L_p \le 0.3 f_{ye} d_b$
Extended strand	$0.2 f_{pye} d_{st}$
Embedded pile	$0.5D$ (see Section 7.4.2.1)
Dowelled	$0.25 f_{ye} d_b$
Hollow dowelled	$0.2 f_{ye} d_b$
External confinement	$0.30 f_{ye} d_b$
Isolated interface	$0.25 f_{ye} d_b$

3.4. Evaluation of platform using vertical piled

The platform is firstly analyzed assuming supported by vertical piles, as a common practice in construction of marine oil platforms. According to the pushover analysis of the structure, as depicted in Figure 14, natural period of the structure and lateral elastic stiffness are 1.99 seconds and 3071.85 kN/m, respectively. The target displacement and base shear are 66cm and 1531 kN, respectively. The plastic hinges with minimum damage are located at the top of the piles. Investigations show that the structure passes acceptable resistance criteria, but is not within the acceptable displacement range. Accordingly, this study focuses on examining the effect of using SMA dampers to reduce displacement.

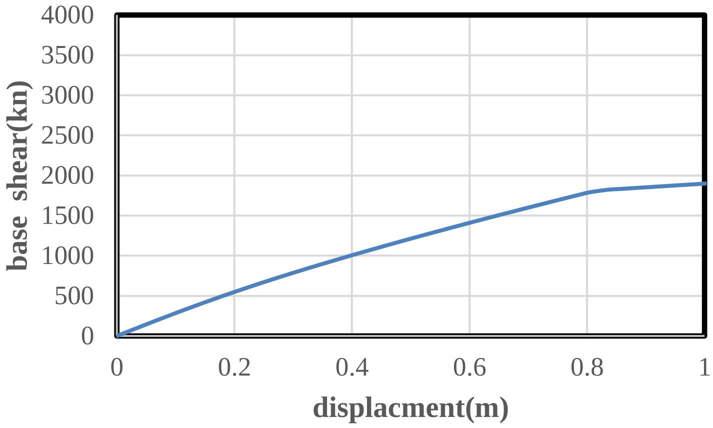


Figure 14. Pushover diagram for the platform with vertical piles.

3.5. Evaluation of platform with combination of vertical and batter piles

Batter piles with slope of 1:6, diameter of 1.3 meters, and thickness of 19 millimeters, are added to the platform, as a common remedy to reduce lateral displacement. 2D elevation of the platform is shown in Figure 15**.**

Figure 15. Schematic combination of vertical and batter piles in platforms.

Based on the pushover analysis, as depicted in **Figure *16***, the target displacement and base shear in this case are 0.215 meters and 3059 kN, respectively. The stiffness of the structure in this configuration is comprehensively higher than the previous case (only vertical piles). Accordingly, the target displacement has been reduced by 1/3 in comparison with the previous case. To obtain a similar displacement without batter piles, its necessary to add several vertical piles to the previous model that is economically unreasonable.

In contrast to the minimal displacements, the high lateral stiffness of the case of direct connection of batter piles to the deck is a major drawback of this system. Because it leads to dramatically increase the seismic demand level of earthquakes. The force in the batter piles during earthquakes can result in buckling, pull out from soil, and damage to the deck, similar to the Chile earthquake. Moreover, from geotechnical perspective, the significant axial force in the batter piles leads to excessive pile penetration into the soil or large number of piles.

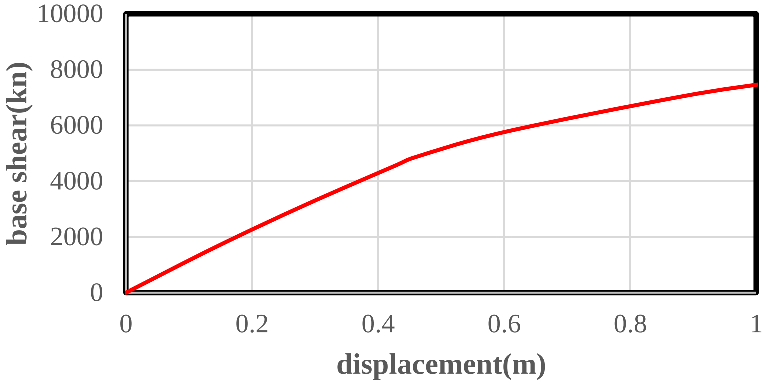


Figure 16. Pushover diagram for the platform with combination of vertical and batter piles.

4. Proposed SMA damper system

In this study, to simultaneously reduce both the seismic demand lateral displacement of the platform, a system of vertical and batter piles with SMA damper is evaluated, as depicted in Figure 17.

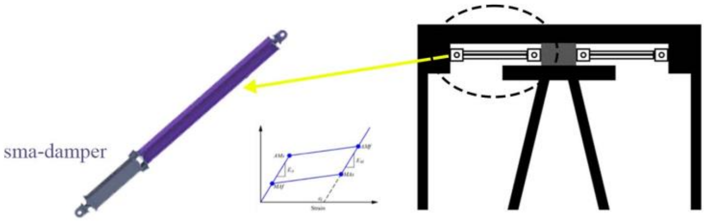


Figure 17. Schematic presentation of platform supported by vertical and batter piles, equipped with SMA dampers.

A multi-linear ideal model is used to represent the behavior of the phases of the shape memory alloy, in this study. For modeling shape memory alloy (SMA) dampers in SAP2000 software, two links should be defined. The first link is used to model elastic behavior, and the second link is a pivot type to consider cyclic behavior of SMA. Material properties of SMA damper, as described in Figure 3, is summarized in Table 4.

Table 4 - Mechanical Specifications of Shape Memory Alloy (SMA)

Mechanical Specifications	Value
Elastic modulus (Austenite and Martensite)	55 GPa
Superelastic strain	6%
Starting stress (Austenite to Martensite)	420 MPa
End stress(Austenite to Martensite)	520 MPa
Starting stress (Martensite to Austenite)	320 MPa
End stress (Martensite to Austenite)	240 MPa

To validate SMA modeling in SAP2000, a single element with an SMA link with the material properties of Table 4 has been modeled, as depicted in Figure 18. The resulted force-displacement diagram is shown in Figure 19, which represents the behavior of the flag-shaped SMA actuator.

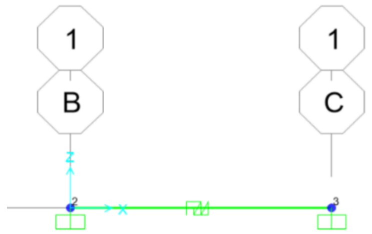


Figure 18. Modeling SMA link in SAP2000

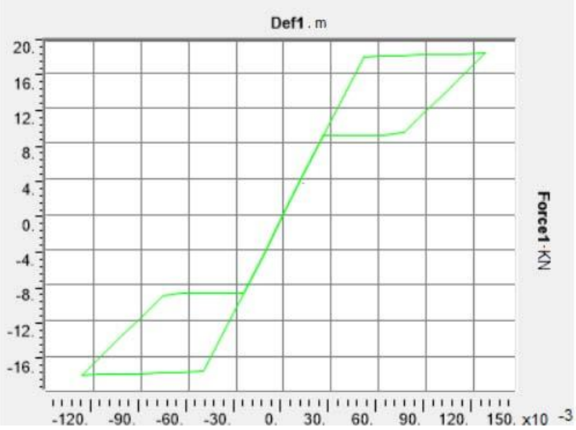


Figure 19. Flag-Shaped force-displacement for SMA damper in SAP2000

The results of the pushover analysis of the platform with SMA damper is shown in Figure 20. The target displacement and base shear for the system with SMA actuator are 21.5 cm and 1236 kN, respectively. As can be seen in this figure, lateral displacement and base shear during the earthquake is considerably reduced with the proposed structural system.

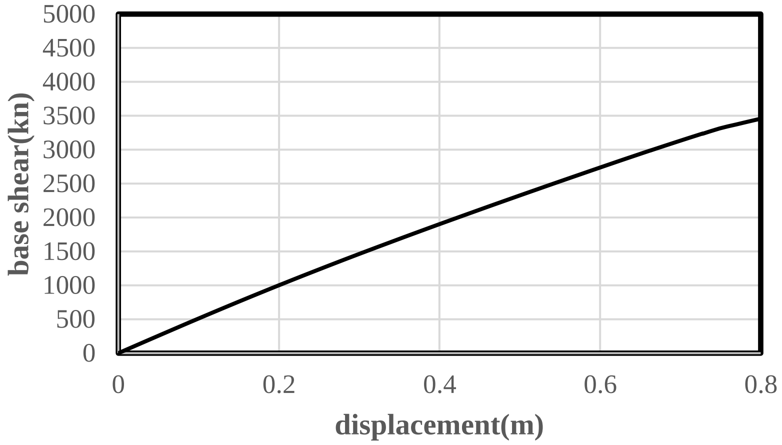


Figure 20. Pushover diagram of the platform with SMA actuator.

Table 5 compares lateral displacement and base shear of the following systems:

Case 1: Only vertical piles
Case 2: Combination of vertical and batter piles as depicted in Figure 15
Case 3: The proposed system with SMA damper as depicted in Figure 17

Comparing the mentioned systems, it can be concluded that the platform equipped with SMA dampers have been able to significantly control lateral displacement and base shear by dissipating the seismic input energy, as a main objective of the present study. For example, the minimum base shear is recorded in SMA system (1236kN) that is 80% and 40% of the base shear in cases 1 and 2, respectively. Similarly, the target displacement of 21.5cm in platform with SMA dampers is analogous to the system with batter piles which is 33% of the case 1. Additionally, no buckling and plastic hinges are seen in the piles.

Table 5. Comparison of pushover results in platform for different structural systems

type model	Effective period(s)	Effective stiffness (kN)	Target displacement (m)	Base shear (kN)
case 1	1.99	3071.85	0.66	1531
case 2	1.797	6387.31	0.215	3059
case 3	1.27	4775.36	0.215	1236

To provide a better comparison between SMA and other types of dampers, a system with friction damper is additionally evaluated. This system is modeled similarly to the viscoelastic dampers, and the FRICRTION link element with specification in Table 6 is employed.

Table 6. Friction damper specifications.

Friction Damper Model	Effective Damping	Shear Force (kN)
FR280	20%	80

The results of the pushover analysis for platform equipped with friction dampers is shown in Figure 21. The target displacement and base shear for the system are 24.5 cm and 1766.5 kN, respectively. The displacement and base shear of the system with friction damper are 14% and 43% more than SMA dampers, that indicate the superiority of the SMA over the friction damper**.**

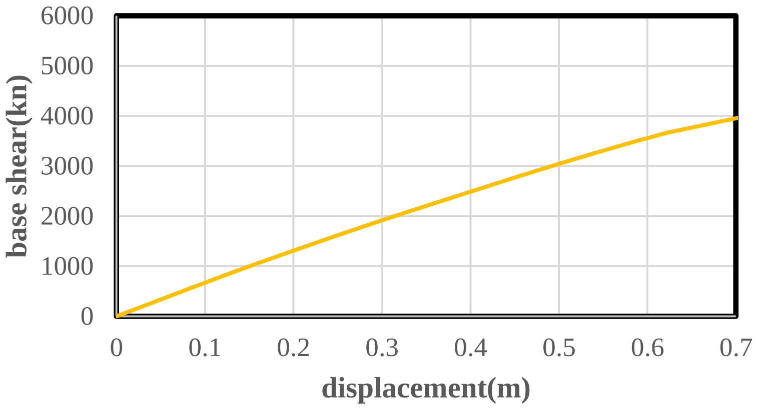


Figure 21. Pushover diagram for platform equipped with friction dampers.

5. Dynamic Analysis

To further investigation and more accurate conclusions, time history analysis is conducted on the platform in three scenarios (as discussed in Table 5) using the seismic acceleration record of Qeshm earthquake, as shown in Figure 22. Figure 23 and Figure 24 compare displacement and base shear, respectively, in different cases described in Table 5.

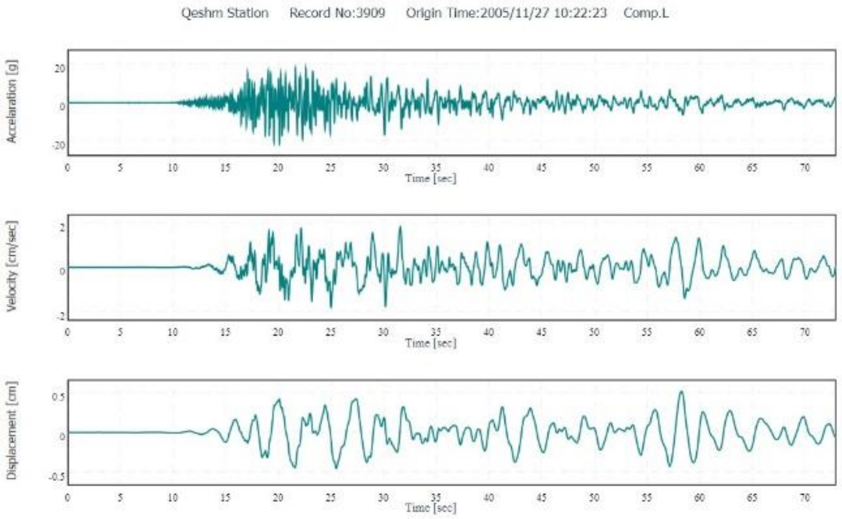


Figure 22. Time history of seismic record of Qeshm earthquake (2005)

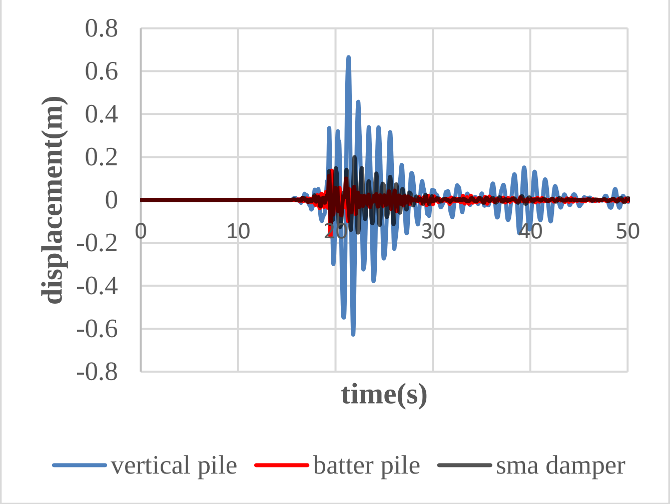


Figure 23. Comparison of displacement in the platform for different systems under Qeshm earthquake

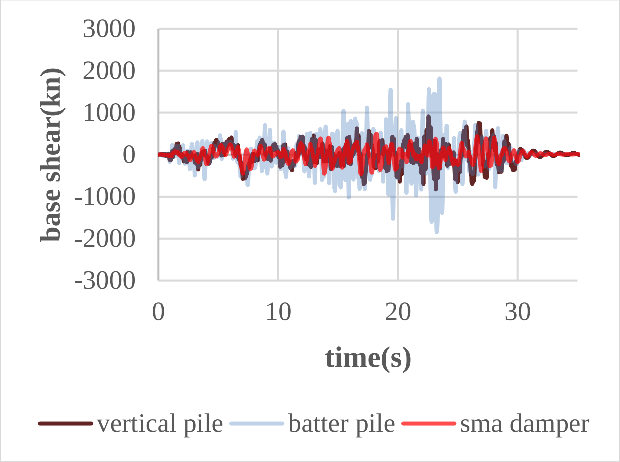


Figure 24. Comparison of base shear in the platform for different systems under Qeshm earthquake

To evaluate the capability of the SMA damper under other time histories, displacement and base shear of the structure under Manjil earthquake is shown in Figures *Figure 25* and *Figure 26*, respectively.

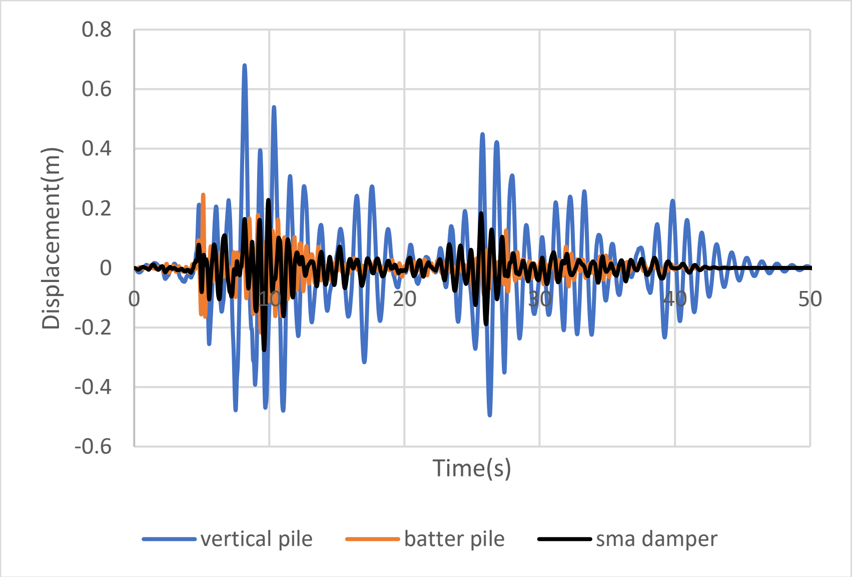


Figure 25. Comparison of displacement in vertical, batter and SMA dampers under Manjil earthquake.

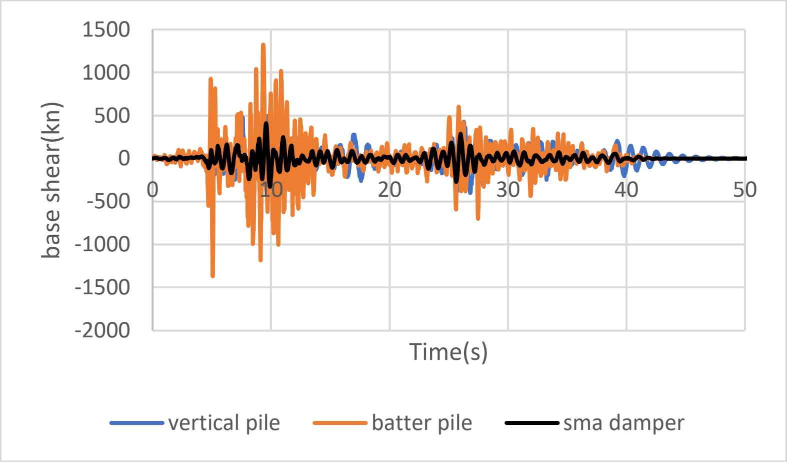


Figure 26. Comparison of base shear in vertical, batter and SMA dampers under Manjil earthquake.

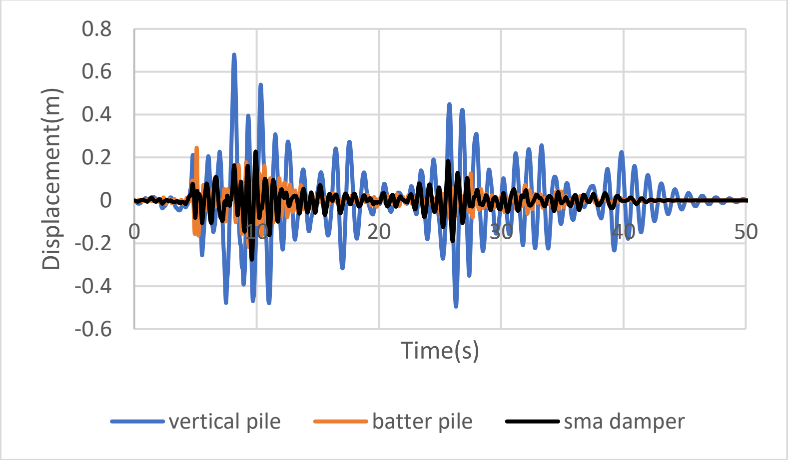


Figure 27. Comparison of displacement in vertical, batter and SMA dampers under Manjil earthquake.

Table 7 presents the seismic parameters obtained from dynamic analysis for different cases (vertical pile, batter piles and SMA systems), under the Qeshm earthquake record. As can be seen in this table, approximately the same results of the static pushover analysis has been achieved. Accordingly, it can be concluded that SMA dampers have led to reduction in displacement (comparable to the results of batter pile systems), and base shear in the proposed system is lower than both common systems of vertical piles and hybrid batter/vertical piles.

Table 7. Maximum displacement and base shear resulted from time history analysis under Qeshm record

Case	Maximum Displacement (m)	Base Shear (kN)
Case 1	0.71	912
Case 2	0.21	1850
Case 3	0.26	596

6. Fixity point theory

Pushover result have been additionally derive based on the fixity point theory in *Figure 28*. As can be seen in this figure, both p-y and fixity point theory are compatible. The hinge pattern based on the fixity point theory for different drifts are shown in Figures 29-31.

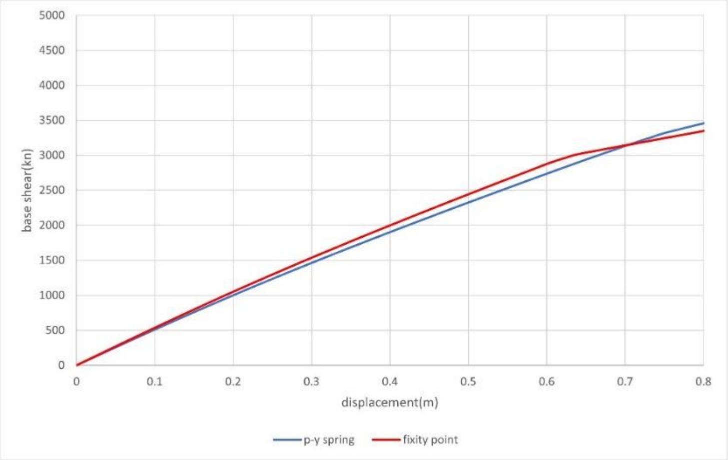


Figure 28. Comparison of pushover results for sma damper between fixity point theory and nonlinear P-Y spring.

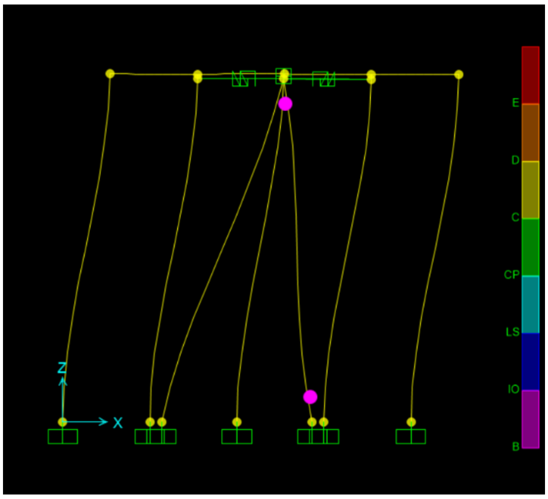


Figure 29. Hinge pattern for drift 42.6mm.

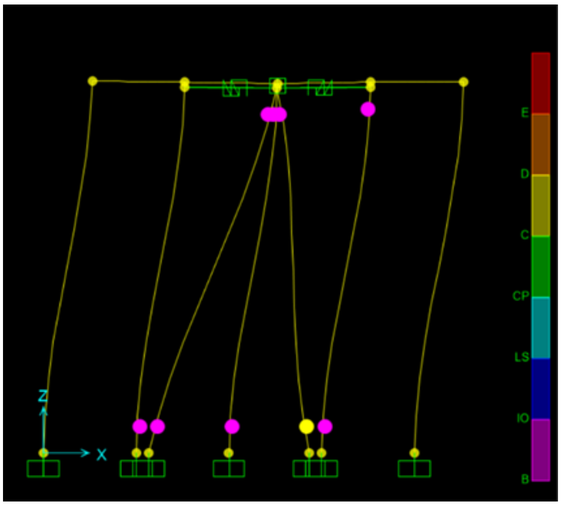


Figure 30. Hinge pattern for drift 110 mm.

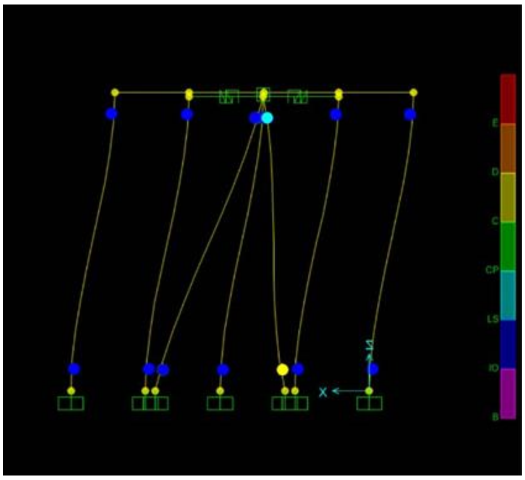


Figure 31. Hinge pattern for drift 208 mm.

7. Conclusion

In this study, a real case of operational platform in Qeshm island with two common pile and deck systems have been examined. In the first system, concrete superstructure is supported by vertical piles. In this case, a desirable flexibility and base shear were obtained, however, considerable resulted displacement was beyond acceptable range of serviceability of the structure. In contract, in the second system with hybrid vertical and batter piles, lower displacement (in acceptable range) with much more base shear (with undesirable failure mechanisms) were observed.

In this research, as an alternative, a system with SMA dampers was proposed to reduce both lateral displacement and base shear in the platform. The results revealed that the SMA damper considerably reduced the lateral displacements and base shear of the platform. Specifically, the following conclusion can be highlighted:

1. Displacements in the platform supported by the (only) vertical piles is in range 60-80cm, which is quite out of acceptable range of serviceability of the structure. Additionally, the base shear in this condition is approximately 1500 kN.
2. By adding batter piles to the platform, the displacement, approximately, is reduced by 70%, which was suitable according to the recommendations. However, in this condition, the undesirable failure mechanisms is seen, with the base shear more than double of the previous case.
3. Proposed system with SMA damper resulted in 59% reduction in base shear compared to batter pile system, and a 67% reduction in displacement compared to the vertical pile configuration. This result shows superiority of SMA damper systems over traditional lateral force systems.

Finally, comparing the SMA with friction dampers, the results show better performance of SMA over friction dampers.

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